Development of Advanced Plasma Simulation Models for Thruster Applications

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Theory and Numerical Simulation I, 1:30pm

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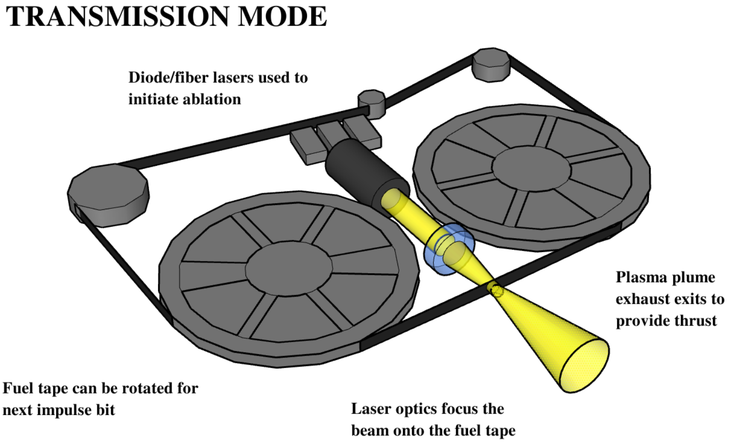
Outline

1. MHD Modeling of Laser Ablation Plasma Thruster
   - The Laser Ablation Plasma Thruster
   - Numerical Simulation Results
2. Shortcomings of the MHD Model
   - Modeling Deficiencies
   - Potential Applications
3. Advanced Fluid Models
   - Single-fluid Magnetohydrodynamics Retaining Maxwell's Equations
   - Two-fluid Magnetohydrodynamics
4. Current Progress and Validation Tests
   - An Implicit, Multidimensional Finite Volume Solver
   - Validation Tests and State-of-the-Art

The Laser Ablation Plasma Thruster

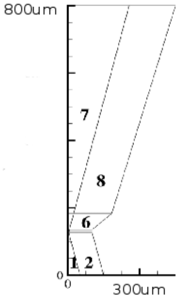
- Subkilogram form of micro- and nanosat propulsion
- Low-power thruster (15-100's W)
- Ablates either a polymer or exothermic fuel tape
- Choice of fuel dictates performance of thruster
  - Important governing physical parameter: Coupling coefficient (Cm)
  - Cm [N/MW] measures effective thrust per megawatt of input laser power.
  - Polymer Cm's are $\approx$100's N/MW.
  - Exothermic Cm's are as high as 3,500 N/MW.
- Polymer operation
  - Cm $\approx$ 100 N/MW, Thrust $\approx$ 1μN, $I_{sp} \approx$ 100s. [1]
- Exothermic operation
  - High-I_{sp} mode: Cm $\approx$ 3,000N/MW, $F_t \approx$ 57mN, $I_{sp} \approx$ 3,660s (measured![1])
  - Low-I_{sp} mode: Cm $\approx$ 3,000N/MW, $F_t \approx$ 6.48N, $I_{sp} \approx$ 116s (measured![1])

The Laser Ablation Plasma Thruster



Modeling the Laser Ablation Plasma Thruster

- Our goal is to model this thruster using an MHD code with laser/plasma interactions.
- We want to construct a model allowing us to:
  - Test different polymer and exothermic propellants
  - Evaluate the overall performance of the fuel selection
  - Predict the overall coupling coefficient for the fuel chosen

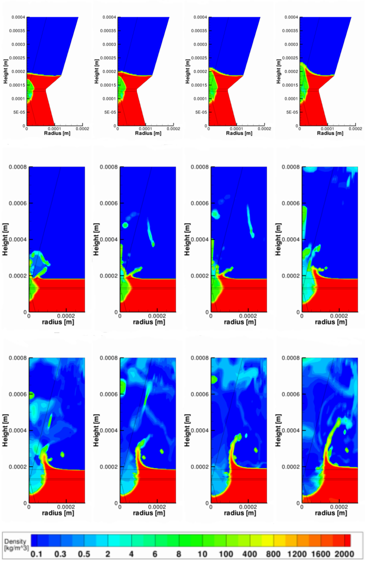


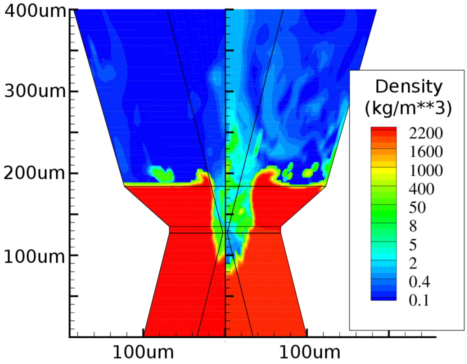
2D Axisymmetric mesh (laser enters from bottom of Block 1)

Allows for:

- Different geometry
- Different laser conditions
- Different propellant
- Resolving transient behavior

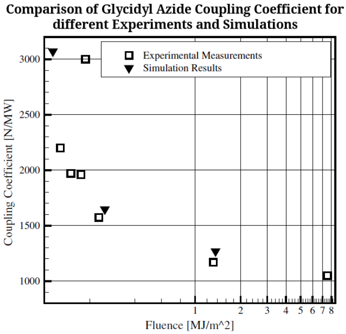
Modeling, cont.





Summary of Laser Ablation Plasma Thruster Modeling

- We have succeeded at modeling both polymer and exothermic propellants.
- We can reach laser energies of ≈10W.
- Changes in geometry result in increased ablation pressure.
- Experimentations in laser-supported detonation and inhibitor fuel tapes.
- Have achieved good agreement with experimental Cm measurements.



Some References...

- "Micropropulsion Using a Laser Ablation Jet." C. Phipps, J. Luke, T. Lippert, M. Hauer, A. Wokaun. Journal of Propulsion and Power vol 20, no. 6, 2004.
- "Laser-powered, Multi-newton Thrust Space Engine with Variable Specific Impulse." C. Phipps, J Luke, W. Helgeson. Proc. of SPIE vol. 7005, 70051X, HPLA VII, 2008.
- "Computer Simulations of Exothermic Propellants in a Micro-laser Ablation Plasma Thruster." R. Thompson, T. Moeller, Journal of Propulsion and Power vol. 28, no. 2, 2012.
- "Computational Investigations of Performance Improvements for Microlaser Ablation Plasma Thrusters Using Nozzles." IEEE Transactions on Plasma Science, vol. 39, no. 11, Nov 2011.
- Thompson, Richard Joel, "Computational Investigations of Characteristic Performance Improvements for Subkilogram Laser Micropropulsion." Master's Thesis, University of Tennessee, 2009. http://trace.tennessee.edu/utk_gradthes/565
- "MACH2 Simulations of a Micro-laser Ablation Plasma Thruster with Nozzles." AIAA-2010-6619. 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference in Nashville, TN, 2010.

Improving Plasma Modeling

- Another aspect of our modeling has been developing structured and unstructured, implicit finite volume plasma solvers.
- This work has focused on retaining the full Maxwell equations.
- This allows us to retain electrodynamic behavior usually seen in kinetic/particle-in-cell (PIC) simulations, which are not usually retained in fluid simulations.
- Particularly:
  - We can resolve net charge densities and charge non-neutralities
  - Can simulate electromagnetic wave propagation
  - Can retain multiple species effects

Improving Plasma Modeling – Telegrapher's Equation

$$\frac{1}{c_0^2}\frac{\partial^2 \mathbf{B}}{\partial t^2} + \mu_0 \sigma \frac{\partial \mathbf{B}}{\partial t} - \nabla^2 \mathbf{B} = 0$$

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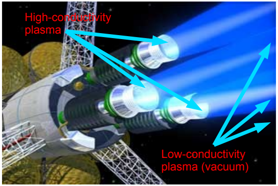
Shortcomings of MHD

The Magnetohydrodynamic model:

- applies well in high-conductivity plasma.
- reduces everything to a single time-scale (fluid).
- assumes quasineutrality of the plasma.
- does not permit displacement current.
- does not permit electromagnetic waves.
- is intrinsically low-frequency
- (does not permit multiple species effects).

Potential Applications

- Plasma space thrusters feature both high- and low-conductivity regions (transition from high-conductivity plasma to vacuum).



- Both high- and low-conductivity regions can lead to ill-posed numerical schemes.
- Plasma actuators and other ‘electrohydrodynamic’ flows feature important charge non-neutralities and multiple species effects.
- Engineering applications in which electromagnetic wave propagation is important (re-entry blackout communications) must resolve these waves.

Advanced Fluid Models

- We are exploring advanced fluid models that retain the full Maxwell equations to solve these problems:
- A single-fluid plasma model with displacement current and Ohm's law,
- A two-fluid plasma formulation

Single-fluid Plasma Model

- Retains Navier-Stokes equations for a single fluid
- Retains full Maxwell equations for electrodynamics
- Current is given by Ohm's law
- Navier-Stokes equations with Lorentz body force can be rewritten in a strong conservative form:

$$\frac{\partial \varrho_{\mathrm{m}}}{\partial t} + \nabla \cdot (\varrho_m \mathbf{u}) = 0$$

$$\frac{\partial}{\partial t}\left(\varrho_m \mathbf{u} + \frac{1}{c_0^2}\mathbf{S}^{em}\right) + \nabla \cdot \left(\varrho_m \mathbf{u}\mathbf{u} + p\bar{\bar{\mathbf{I}}} - \nabla \cdot \bar{\bar{\boldsymbol{\Sigma}}}^{visc} - \nabla \cdot \bar{\bar{\boldsymbol{\Sigma}}}^{em}\right) = 0$$

$$\frac{\partial}{\partial t}\left(\mathcal{E} + u^{em}\right) + \nabla \cdot \left(\left[\mathcal{E} + p\right]\mathbf{u} + \mathbf{S}^{em} + \mathbf{q} - \bar{\bar{\boldsymbol{\Sigma}}}^{visc} \cdot \mathbf{u}\right) = 0$$

- Can resolve higher-frequency behavior and full electromagnetics, may be able to resolve Langmuir oscillations
- Is limited in explicit simulations to a timestep of $\approx \epsilon_0/\sigma$
- Implicit simulations can achieve very large timesteps

Two-fluid Plasma Model

- Retains a set of Navier-Stokes equations per species (usually ions and electrons)
- Retains full Maxwell equations for electrodynamics
- Current is given by convective current, $\mathbf{j}_e = (e/m)\varrho_e \mathbf{u}$
- Can resolve multiple species effects, Langmuir oscillations, higher-frequency behavior and full electromagnetics
- Is limited by the smallest of the light transit time, plasma frequency and cyclotron frequency.
- Can be very stiff in high-conductivity plasma.
- Captures more essential physics, but at the cost of high computational expense.

Finite Volume Solver

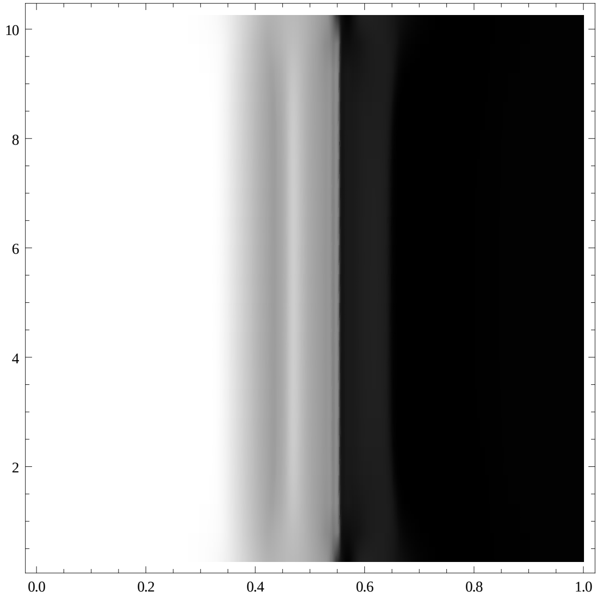
- To implement both of these plasma models, we have developed a structured, multidimensional implicit finite volume plasma solver.
- An unstructured version is under way.
- Implements a dual-time implicit scheme, which allows for preconditioning in the dual-timestep.
- Current permits a flux splitting method, Roe approximate Riemann solver method, and hybrid flux-split Roe method.
- Currently works in both 1D and 2D.
- We are validating the solver against multiple 1D and 2D tests.
- We are testing it on both high and low conductivity (and mixed) problems to demonstrate validity across full range of conductivity.

Brio and Wu Shock Tube Problem

- The Brio and Wu shock problem has become a classic MHD (and two-fluid) benchmark problem
- We solve the Brio and Wu shock problem in 2D.
- Domain was one unit length long and ten unit lengths tall.
- Initial conditions:

$$\left\{\begin{array}{c} \varrho_m \\ u \\ v \\ w \\ P \\ \hline b_x \\ b_y \\ b_z \\ e_x \\ e_y \\ e_z \end{array}\right\}_{\text{Left}} = \left\{\begin{array}{c} 1 \\ 0 \\ 0 \\ 0 \\ 1 \\ \hline 0.75 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{array}\right\}, \qquad \left\{\begin{array}{c} \varrho_m \\ u \\ v \\ w \\ P \\ \hline b_x \\ b_y \\ b_z \\ e_x \\ e_y \\ e_z \end{array}\right\}_{\text{Right}} = \left\{\begin{array}{c} 0.125 \\ 0 \\ 0 \\ 0 \\ 0.1 \\ \hline 0.75 \\ -1 \\ 0 \\ 0 \\ 0 \\ 0 \end{array}\right\}$$

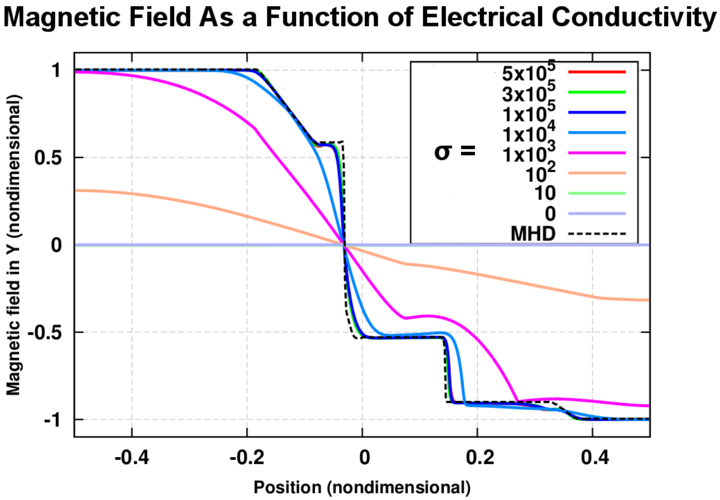
Brio and Wu Shock Tube Problem



Brio and Wu Shock Tube Problem

movie...

Brio and Wu Shock Tube Problem



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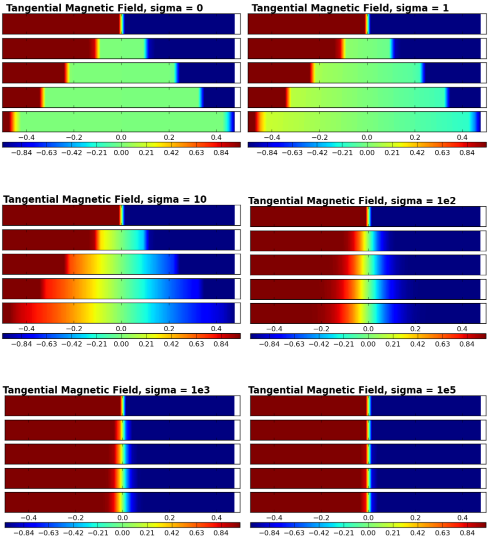
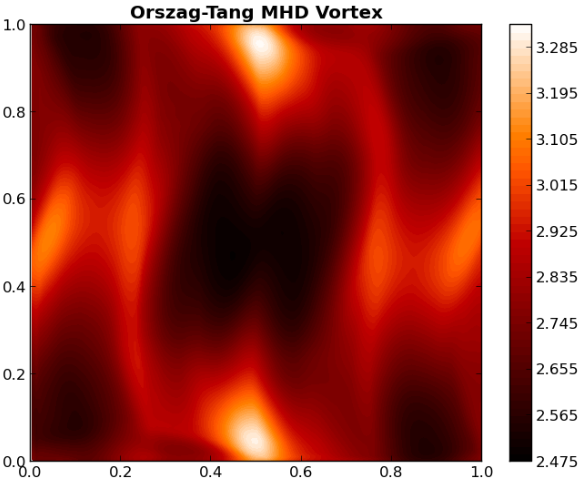


Orszag-Tang MHD Vortex Problem

- Tests MHD turbulence capabilities
- We solve the problem in 2D.
- Our boundary conditions differ from the usual periodic conditions (simply not implemented yet).

Orszag-Tang MHD Vortex Problem



Some References...

- R. J. Thompson, T. Moeller, and C. L. Merkle, “A Strong Conservation Formulation for Finite Volume Plasma Simulations with Displacement and Conduction Current,” in 43rd AIAA Plasmadynamics and Lasers Conference, New Orleans, LO, June 25-28, 2012, 2012
- Li, D., Zeng, X., Merkle, C., Felderman, E., and Sheeley, J., “Coupled Fluid-Dynamic Electromagnetic Modeling of Arc Heaters,” 37th AIAA Plasmadynamics and Lasers Conference, 2006.
- Li, D., Merkle, C., Scott, W. M., Keefer, D., Moeller, T., and Rhodes, R., “A Hyperbolic Algorithm for Numerical Solutions of Coupled Plasma/EM Fields Including Both Real and Displacement Currents,” 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 2007.
- Li, D., Merkle, C., Scott, W. M., Keefer, D., Moeller, T., and Rhodes, R., “Hyperbolic Algorithm for Coupled Plasma/Electromagnetic Fields Including Conduction and Displacement Currents,” AIAA Journal, Vol. 49, No. 5, 2011, pp. 909â920.
- Brio, M. and Wu, C. C., “An Upwind Diverencing Scheme for the Equations of Ideal Magnetohydrodynamics,” Journal of Computational Physics, Vol. 75, 1988, pp. 400–422.

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